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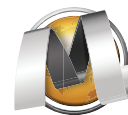
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### Marchenko Imaging of Volve Field, North Sea

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## SUMMARY

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Marchenko redatuming estimates the full response (including internal multiples) from a virtual source inside of an medium, using only reflection measurements at the Earth's surface and a smooth estimate of the velocity model. As such, it forms a new way to obtain full field propagators to form images of target zones in the subsurface by means of Marchenko imaging, without necessarily have to create detailed models of overburden structure.

One of the main obstacles to the application of such novel techniques to field datasets is the set of requirements of the reflection response: it should be wideband, acquired with wide aperture, densely sampled arrays of co-located sources and receivers, and should have undergone removal of direct waves, source and receiver ghosts and free-surface multiples. We use a wave-equation approach to jointly redatum, demultiple, and source designation to transform data recorded using ocean-bottom acquisition systems into a suitable proxy of the reflection response required by the Marchenko scheme.

We briefly review the Marchenko redatuming scheme, and present the first encouraging field results of 2D target-oriented imaging of an ocean-bottom cable dataset, acquired over the Volve field. We further discuss the 'challenge of convergence' of the Marchenko redatuming scheme for real data.

## Introduction

Marchenko redatuming (or autofocus) is a novel technique to estimate acoustic or elastic wavefields in the subsurface including primaries and multiples from reflection measurements at the Earth's surface and a smooth estimate of the propagation velocity (Broggini et al., 2012; Wapenaar et al., 2013; Wapenaar and Slob, 2014; da Costa et al., 2014). Advantages over standard redatuming techniques based on time-reversal of incomplete data (i.e., data recorded along an open boundary of receivers) are essentially that an accurate reconstruction of the wavefield coda (or internal multiples) in the down-going field is produced, non-physical events in up-going field are removed, amplitudes are balanced, and the retrieved field is separated into its up- and down-going components.

As a consequence of the more accurate estimation of internal multiples, Marchenko fields can be used to improve subsurface imaging in areas where reverse-time migration (RTM) generates spurious structures caused by incorrectly handled internal reflections. Broggini et al. (2014) construct an image free from internal multiples by cross-correlating (or deconvolving) the retrieved up- and down-going fields at any point in the subsurface. Wapenaar et al. (2014) limit this computation to a chosen depth level and create redatumed reflection responses free of spurious events related to internal multiples in the overburden (underburden) that form the basis for obtaining accurate images of a target zone below (above) the depth level of interest.

This paper presents the first successful application of Marchenko redatuming and imaging to a real dataset. We use data from a 2D line of the Volve ocean-bottom cable (OBC) dataset, acquired offshore Norway in 2002, and we propose a processing workflow to obtain a single-sided reflection response that satisfies the requirements of the Marchenko scheme. We then compare images from standard RTM to those that we obtain by performing target-oriented imaging using Marchenko fields.

## Marchenko equations

Marchenko redatuming is based on two Green's function representations (Wapenaar et al., 2014) that can be discretized as (van der Neut et al., 2014)

$$\mathbf{g}^- = \mathbf{R}\mathbf{f}^+ - \mathbf{f}^-, \quad \mathbf{g}^+ = -\mathbf{R}\mathbf{Z}\mathbf{f}^- + \mathbf{Z}\mathbf{f}^+. \quad (1)$$

Here,  $\mathbf{g}^-$  and  $\mathbf{g}^+$  are the up- and down-going estimated fields, respectively, with sources at the acquisition surface and receivers at desired subsurface image points. The so-called focusing functions  $\mathbf{f}^-$  and  $\mathbf{f}^+$  are respectively up- and down-going acausal solutions to the wave-equation that at zero-time focus at the subsurface point. We suppose that  $\mathbf{f}^+ = \mathbf{f}_d^+ + \mathbf{f}_m^+$ , that is,  $\mathbf{f}^+$  is composed of a direct wave  $\mathbf{f}_d^+$  and a down-going coda  $\mathbf{f}_m^+$ : these quantities are organized in vectors with concatenated traces in the time-space domain. Matrix  $\mathbf{R}$  contains the real Earth's reflection response, and (left-)multiplication is equivalent to performing multi-dimensional convolution in the time-space domain.  $\mathbf{Z}$  acts on a vector by rearranging its elements to mimic time-reversal. To obtain a system of coupled Marchenko equations, a muting function  $\mathbf{M}$  that removes the direct arrival and all events after this arrival is applied to equations 1 (Wapenaar et al., 2014) yielding,

$$\mathbf{f}^- = \mathbf{M}\mathbf{R}\mathbf{f}_d^+ + \mathbf{M}\mathbf{R}\mathbf{f}_m^+, \quad \mathbf{Z}\mathbf{f}_m^+ = \mathbf{M}\mathbf{R}\mathbf{Z}\mathbf{f}^-. \quad (2)$$

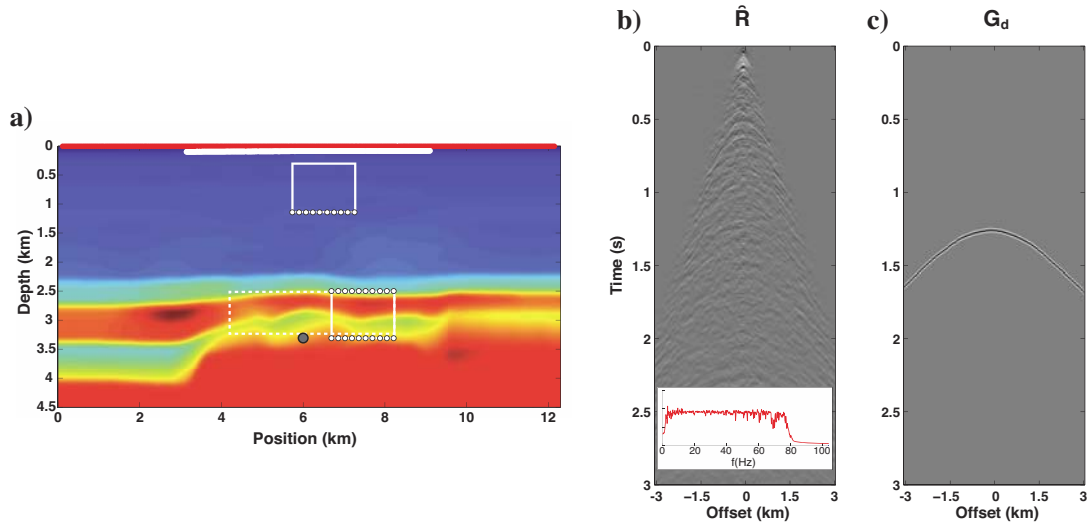
Starting from an initial focusing function  $\mathbf{f}_d^+$ , obtained by time-reversing an estimate of the direct wave  $\mathbf{G}_d$ , equations 2 can be iterated to convergence. Finally, up- and down-going Green's function can be computed from equations 1 using the estimated focusing functions  $\mathbf{f}^-$  and  $\mathbf{f}^+$ .

## Marchenko inputs and redatumed fields

Marchenko redatuming imposes severe requirements on the reflection response  $\mathbf{R}$ , and the actual reflection data can only be used as a proxy after some pre-processing.  $\mathbf{R}$  is assumed to have been obtained from infinitely extended fixed-spread receiver arrays with dense source coverage over the entire spread, to have infinite bandwidth, and to contain only primary reflections and internal multiples (i.e., is deprived of direct waves, source and receiver ghosts, and surface-related multiples). If data are acquired with standard ocean-bottom acquisition systems (Figure 1a), wave-equation approaches to joint source redatuming (at the receiver level), demultiple, and source signature (Amundsen, 2001) can transform the recorded data into a suitable estimate of the reflection response

$\hat{\mathbf{R}}$  for Marchenko redatuming. The essence of these methods is to solve by means of multi-dimensional deconvolution (Wapenaar et al., 2011) an integral relationship between the recorded up- and down- decomposed data and the desired data that would be recorded in a hypothetical seismic experiment with no sea surface present, to retrieve an estimate of the latter (Figure 1b).

An estimate of the direct arriving wavefront is also required to create the initial focusing function  $\mathbf{f}_d^+$ . This can be computed by forward modeling (e.g., ray-tracing, finite-differences) using a smooth velocity model such as that shown in Figure 1a. We compute the traveltime of the first arriving wavefront from a subsurface point  $\mathbf{x}_F = \{6, 3.3\}$  km via ray-tracing and apply a 40Hz Ricker wavelet with constant amplitude for all offsets (Figure 1c). Focusing functions  $\mathbf{f}^+$  and  $\mathbf{f}^-$  estimated after three iterations of Marchenko equations 2 are shown in Figures 2a, b, and used in equations 1 to compute Green's functions  $\mathbf{g}^+$  and  $\mathbf{g}^-$  (Figures 2c, d). Note that the iterative Marchenko scheme has retrieved the coda in the down-going field. An event with similar move-out to the direct arrival is visible at zero-offset around 1.5s in Figure 2c; this is possibly an internal multiple experiencing multiple bounces in the high velocity layer in between 2.6 and 2.85 km depth.



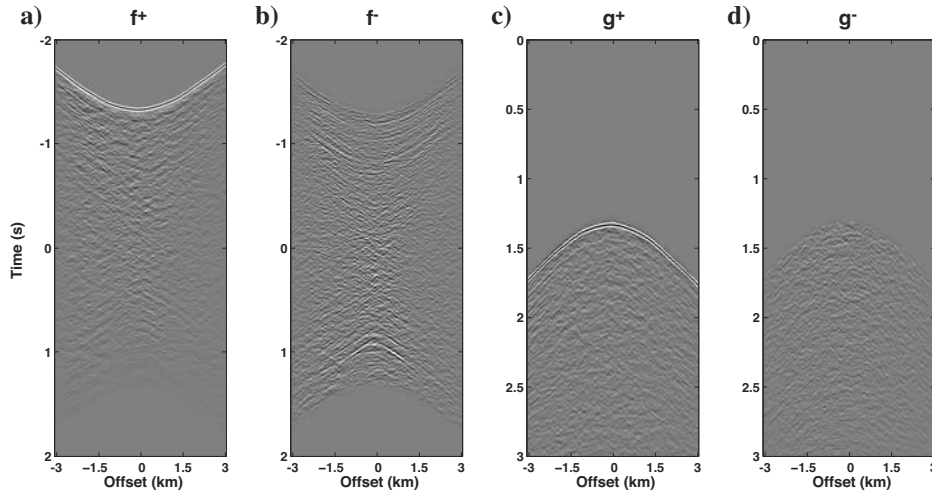
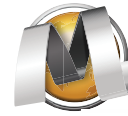
**Figure 1** a) Migration velocity model, source array at  $z_S = 6$  m (red line) and receiver array at  $z_R = 90$  m (white line) in the ocean-bottom cable acquisition. The grey dot represents the subsurface point where Marchenko fields are computed and shown in Figure 2, while two white boxes and one dashed box indicate the target areas where Marchenko imaging is performed. b) Estimate of the reflection response  $\hat{\mathbf{R}}$  and its average amplitude spectrum (see insert). c) Forward-modelled first arriving wave.

### Marchenko imaging, a tool for target-oriented imaging

Marchenko redatuming is now used to retrieve up- and down-going Green's functions for 151 subsurface points forming an array 1.5 km wide at a depth level of 2.5 km (right lower box in Figure 1). From these fields we obtain an estimate of the reflection response from above the target ( $\mathbf{R}_U$ ) as if both sources and receiver were located along the array of subsurface points and placed in a modified medium with the same properties as the physical medium below the array but homogenous above (Wapenaar et al., 2014):

$$\mathbf{g}^- = \mathbf{g}^+ \mathbf{R}_U \quad (3)$$

Figure 3a shows an estimate of  $\mathbf{R}_U$  for a source in the centre of the subsurface array computed by solving equation 3. As discussed extensively in Wapenaar et al. (2014), the redatumed reflection response can be used as input for standard imaging in a target zone just *below* the redatumed level (Figure 3c). Comparison with standard reverse-time migration of our estimate of  $\hat{\mathbf{R}}$  (i.e., up-going field without source and receiver ghosts and free-surface multiples) shows that Marchenko imaging from above is able to produce an image of similar quality of that from RTM (Figure 3e), slightly improving the details in between the main reflectors at 2.6 and 2.9 km and limiting the (expensive) finite-difference computation to a much smaller subsurface area. While the computational advantage could already represent a reason to perform Marchenko imaging, by allowing target-oriented, high-resolution imaging with much higher frequencies and spatial sampling than RTM can achieve, the



**Figure 2** Marchenko redatuming. a) Down- and b) up-going focusing functions, and c) down- and d) up-going redatumed fields at  $\mathbf{x}_F$ . All panels are displayed with 50% clipping of absolute amplitudes.

focusing functions  $\mathbf{f}^-$  and  $\mathbf{f}^+$  can also be combined to obtain a second image of the reflection response which illuminates the target area from below ( $\mathbf{R}_\cap$ )

$$-\mathbf{Z}\mathbf{f}^- = \mathbf{f}^+\mathbf{R}_\cap \quad (4)$$

An estimate of  $\mathbf{R}_\cap$  for a source in the centre of the subsurface array at a depth level of 3.3 km is shown in Figure 3b, and used to perform standard imaging in a target zone just *above* the lower redatumed level (Figure 3d). Complementary details are provided by reflections illuminating this portion of the subsurface from below and contained in  $\mathbf{R}_\cap$ . Similarly, Marchenko fields are now computed along a line at 1.13 km (upper box in Figure 1) to image the complex stratigraphy in the shallow subsurface from below (Figure 3f and g). To improve the resolution and avoid spatial aliasing, the image is sampled every 5m and compared to that from RTM which was originally sampled every 10m to save computational cost. Finally, Marchenko imaging from below is performed for two additional subsurface lines at 3.3 km depth (left lower box in Figure 1), and the resulting images are merged with the image in Figure 3d to form Figure 4b. Green arrows highlight perfect continuity of reflectors between the different Marchenko images. Marchenko imaging (from below) reveals a coherent structure (blue arrows in Figure 4b) which is not visible, or perhaps is distorted, in the RTM image of the reflection response  $\hat{\mathbf{R}}$  (Figure 4a).

## Discussion and Conclusion

A challenge that we will always face when applying Marchenko redatuming to a field dataset is represented by the convergence of the iterative scheme presented above. Since we do not have direct access to the real Earth's reflection response  $\mathbf{R}$ , it is inevitable to expect that the processed version of the recorded data  $\hat{\mathbf{R}}$  may be scaled differently, such that  $\hat{\mathbf{R}} = k_R\mathbf{R}$  where  $k_R$  is an unknown scalar that depends on the acquisition and processing chain. While one may manually tune  $k_R$  to obtain a coda of comparable amplitude to the direct arrival, an optimal way of estimating  $k_R$  has not yet been developed, but is of paramount importance to the automation of this method. A pragmatic solution has been recently proposed by van der Neut et al. (2014) that developed an adaptive scheme to enforce the cancellation of non-physical events in up-going field.

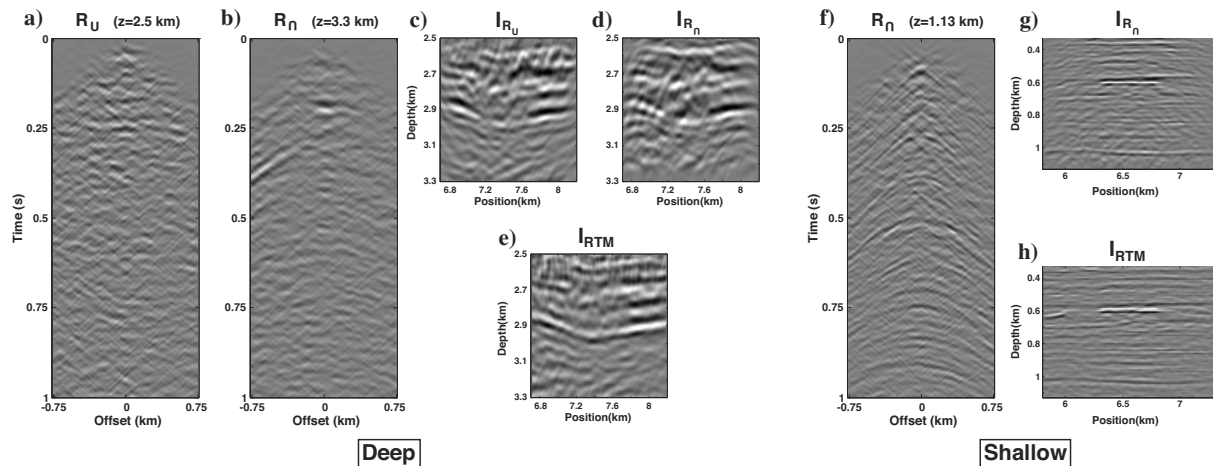
In conclusion, we have proposed a workflow to generate an estimate of the Earth's reflection response  $\mathbf{R}$  for Marchenko redatuming, and used it to produce encouraging results of target-oriented imaging. With this technique, we have produced images of both shallow stratigraphy and deep structures, the latter revealing a coherent structure that is distorted in the RTM image.

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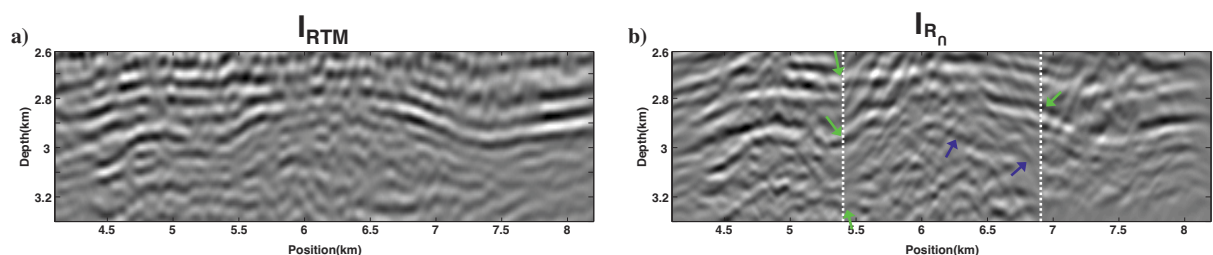
Bayerngas Norge, for the release of the Volve data. We are particularly grateful to G.R.Hall and H.A. Seter from the Statoil Volve team for help and support in the interpretation.



**Figure 3** Marchenko imaging. Multi-dimensional deconvolution estimates of a) reflection response from above  $\mathbf{R}_U$  at depth level  $z=2.5$  km and b) reflection response from below  $\mathbf{R}_n$  at depth level  $z=3.3$  km. Images of the target zone from c) above and d) below, compared to that obtained from e) standard RTM of the reflection response  $\hat{\mathbf{R}}$ . f), g), and h), same as b), d), and e) for a shallower depth level ( $z=1.13$  km).

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**Figure 4** Merging of Marchenko images. a) Standard RTM of the reflection response  $\hat{\mathbf{R}}$  and b) Marchenko imaging from below of three different subsurface redatumed  $\mathbf{R}_n$  fields (white dashed lines delimit the three images). Blue arrows in b) indicate a structure revealed by Marchenko imaging that is not visible in the RTM image. Green arrows in b) indicate near-perfect continuity between images.